ELECTROHYDRODYNAMIC ENHANCED TRANSPORT AND TRAPPING OF AIRBORNE PARTICLES TO A MICROFLUIDIC AIR-LIQUID INTERFACE

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ABSTRACT

We introduce a novel approach for greatly improved transport and trapping of airborne sample to a microfluidic analysis system by integrating an electrohydrodynamic (EHD) air pump with a microfluidic air-liquid interface. In our system, a negative corona discharge partially ionizes the air around a sharp electrode tip while the electrostatic field accelerates airborne particles towards an electrically grounded liquid surface, where they absorb. The air-liquid interface is fixated at the microscale pores of a perforated silicon diaphragm, each pore functioning as a static Laplace valve. Our system was experimentally tested using airborne smoke particles of ammonium chloride and aqueous salt solution as the liquid. We measured that EHD enhanced transport of the particles from the air into the liquid is enhanced over 130 times compared to passive trapping.

1. INTRODUCTION

Detection, monitoring, and public surveillance of airborne particles and molecules are of great importance for today's security, health care, environment, industrial and military monitoring activities. Particles of particular interest are chemical compounds such as explosives, drugs and toxins, different pollutants and contaminants, and pathogens e.g. bacteria, virus and fungi. Sample-to-liquid interfacing is required in all systems where chemical analysis of airborne particles and substances is performed in liquid environment. Analysis of liquid aggregates is by far the most common analysis form, but the substance of interest is often airborne. Previously shown air sample interfaces for μ TAS applications rely on passive trapping of particles to a

free liquid surface [1, 2] or to a solid surface which can be washed with liquid to collect particles [3, 4].

It has been known for decades that active transport of airborne particles can efficiently be achieved by using corona systems [5]. A large positive or negative voltage (kV) is applied to a high-curvature solid corona electrode which is located opposite to a low-curvature solid collector electrode. The collector is set to ground or a low voltage and an electrostatic field is created between the two solid objects. The high field at the corona electrode causes avalanche breakdown, leading to generation of free electrons and ions. Ions of opposite charge to the corona electrode are accelerated in the electric field towards the collector electrode. Upon collision between traveling ions and neutral molecules and particles, momentum is transferred leading to a drag force on the bulk air towards the collector. Hence, there is a net movement of airborne molecules and particles from the solid corona electrode towards the collector electrode.

Several applications have been shown using different corona systems, e.g. air precipitators [6], dehumidifiers [7], thrusters [8], and cooling devices for electronics [9]. Miniaturized corona systems have been reported in [10, 11], and a system for capturing sub- μ m bioparticles in air, such as virions, was shown in [12].

The objective of this work was to actively enhance and promote transport of airborne particles to a liquid interface of e.g. a microfluidic system, by using a liquid based collector electrode. In addition to transportation, the aim was also to study the absorption of the particles to the liquid, for further analysis in the liquid environment.

Figure 1: a schematic of the experimental setup. The corona electrode ionizes surrounding air molecules and particles through a high voltage corona discharge. The charged species accelerate in the electric field and drag along uncharged particles towards the liquid collector electrode. When they reach the air-liquid interface they impact and become absorbed. Generated smoke particles were used for visualization and quantification.

2. DESIGN AND FABRICATION

To promote active transportation of airborne particles to an air-liquid interface, we developed a corona system where the conventional solid collector electrode is replaced with a liquid electrode, see figure 1. The liquid electrode, consisting of an aqueous salt solution, is used together with a corona needle electrode in air. Upon applied corona discharge voltage, airborne molecules and particles are accelerated towards the air-liquid interface of the liquid based collector where they impact.

In this system, a perforated silicon diaphragm is employed to sustain a stable air-liquid interface. Previous work has successfully reported how such diaphragm design was used in an electronic nose to sense narcotics [2]. The diaphragm contains 18,000 perforations, separated by 10 μm and each with a diameter of 25 μm , distributed over a total area of 20 mm^2 . The bulk silicon gives the diaphragm mechanical stability while surface tension ensures a stable air-liquid interface, i.e. each pore functions as a static Laplace valve. This design offers good tolerance against pressure fluctuations, both unintended and intended such as when refilling or rinsing the system; it discriminates large particles from entering the liquid domain; and keeps the air-liquid interface at a defined position with respect to the liquid container. The diaphragm is fabricated from a silicon-on-insulator (SOI) wafer with standard micromachining techniques, described in [2].

A liquid container in conjunction with the interface is fabricated in plastics, with an electrically grounded liquid-metal wire interconnection and a liquid fill port. The system contains 150 μl of liquid (0.9 % w/v sodium chloride in DI water). It is attached to the backside of a carrier substrate of polymethyl methacrylate (PMMA). The silicon diaphragm is attached to the front side of the carrier by double-sided adhesive tape and covered by non-conductive tape, only exposing the perforated air-liquid interface. The interface is aligned with the liquid

container on the backside to expose the liquid to open air. Figure 2 shows the fabricated collector chip and the perforated silicon diaphragm.

3. EXPERIMENTS

To experimentally investigate the potential of the liquid collector electrode in the corona system, two commercially available smoke types are used to represent and visualize airborne particles. One type is made of ammonium chloride (Splintax, Björnax AB, Sweden), NH_4Cl , a water soluble molecule that easily absorbs at the air-liquid interface. The amount of absorption can be monitored by measuring the decrease in pH of the liquid due to deprotonation of ammonium ions forming ammonia, following the equilibrium reaction:

The other type of smoke is made of octadecanoic acid (Smoke-pen, Björnax AB, Sweden), $\text{CH}_3(\text{CH}_2)_{16}\text{COOH}$, a fatty acid also known as stearic acid, which is not water soluble but better visible than the former. According to the manufacturer, both smoke types consist of particles in the range of 0.1-1 μm , most likely in the form of agglomerates.

The corona needle electrode is positioned vertically aligned to, and horizontally 15 cm away from, the air-liquid interface of the collector electrode. The smoke generator is placed in between the electrodes, 5 cm from the air-liquid interface in horizontal position. The source generating ammonium chloride smoke, used for measurements, is positioned 10 cm below the electrodes and the source for stearic acid smoke, used for visualization, is positioned 3 cm below. The setup is accommodated in a closed box of PMMA to ensure minimal effects of convective or turbulent air flow from the surroundings.

Figure 2: Middle: photograph of the liquid electrode and its package. Left: the silicon component consisting of a rigid frame which holds a perforated diaphragm, adapted from [1]. Right top: the liquid side of the diaphragm is connected to a plastic tube, containing 150 μl 0.9 % w/v $\text{NaCl}(\text{aq})$ in direct contact with the grounded metal electrode. Right down: the frame of the interface is covered with non-conductive tape to ensure only exposing the diaphragm as the collector electrode area.

A negative corona is generated by applying a DC voltage of $U = -16$ kV to the corona electrode. Subsequently, the smoke source is triggered to generate smoke. One shot lasts for 30 s and the movement of the smoke towards the air-liquid interface is visually inspected. When ammonium chloride smoke is used, pH measurements are conducted on the solution in the liquid container.

4. RESULTS

The active transport of airborne smoke particles towards the air-liquid interface was successfully visualized. Figure 3 shows a fine laminar flow of warm smoke rising upwards due to natural convection when the corona system was turned off. When a voltage was applied and a corona discharge was generated, the smoke was accelerated towards the liquid collector electrode where the particles impact at the interface. The flow speed of the accelerated smoke was visually estimated to approximately 7 cm/s.

The air-liquid interface was visually inspected after each test. In figure 4, a non-used collector device is shown and compared to devices that have been exposed to the different types of smoke. As anticipated, the ammonium chloride was absorbed and dissolved in the liquid while stearic acid did not dissolve but stayed adsorbed at the interface.

The active transport of airborne particles into the liquid was verified by measuring a shift of acidity in the liquid caused by absorbed particles of ammonium chloride according to (1), see table 1. In the presence of smoke but in the absence of a corona enhanced transport, no change in acidity could be measured after 30 s (i.e. one shot of smoke). If the exposure of smoke was increased ten times to 300 s (i.e. ten shots of smoke), a shift of acidity from pH 4.5 to almost 4.0 was measured in the liquid. This corresponds to approximately 0.1 g of ammonium chloride particles being absorbed into the liquid (calculation based on $K_a = 5.6 \cdot 10^{-10}$ for NH_4^+). When a corona voltage was applied to the system to enhance transportation and trapping of the airborne particles, a shift from pH 4.5 to 3.5 was measured within

only 30 s of exposure (i.e. 1 shot of smoke). This shift corresponds to absorption of approximately 1.3 g of smoke particles into the liquid.

Without corona discharge

With corona discharge

Figure 3: frames from video recordings with EHD promoted transport and trapping. Left: without corona discharge, the smoke is moving straight up. Right: with corona discharge, the smoke is accelerated towards the air-liquid interface. Note: the corona needle electrode is outside the picture frame on the left side.

Air-liquid interface, non-used

After exposure of NH_4Cl

After exposure of $\text{CH}_3(\text{CH}_2)_{16}\text{COOH}$

Figure 4: photographs of the air-liquid interface. Left: before usage. Middle: after exposure to smoke of ammonium chloride; the particles dissolve in the liquid and no remains are left at the interface. Right: after exposure to smoke of stearic acid; the particles of the fatty acid, which are insoluble in the liquid, remain at the interface. A concentration gradient of particles in a radial pattern towards the exposed air-liquid interface is visible.

Thus, transportation and trapping of airborne molecules to an air-liquid interface are estimated to be over 130 times more efficient when using the reported corona system compared to a passive system.

Table 1: shift in acidity in the collector liquid measured in pH and calculated mass of absorbed smoke particles for different times of exposure to smoke, with and without an applied corona discharge voltage.

Exposure time	Corona off		Corona on	
	pH	Calc. mass	pH	Calc. Mass
0 s	4.5	0 g	4.5	0 g
30 s	4.5	0 g	3.5	1.3 g
300 s	4.0	0.1 g	not measured	

5. CONCLUSIONS

This work shows that EHD enhanced transport and trapping of airborne particles to a microfluidic air-liquid interface is improved by over 130 times compared to passive transportation and trapping. Furthermore, a liquid based collector electrode is successfully used in conjunction with a corona discharge electrode surrounded by air. A stable air-liquid interface is realized by using a perforated silicon diaphragm with each pore functioning as a static Laplace valve. This opens up possibilities to integrate microfluidic analysis systems with air sampling instruments for rapid and efficient analysis of airborne particles.

6. ACKNOWLEDGEMENT

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